The TREND IN ENGINEERING

at the University of Washington

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ESTIMATION OF MAXIMUM RUNOFF BY MEANS OF AERIAL PHOTOGRAPHS

A PHOTOELASTIC STUDY OF STRAIN-ENERGY STORAGE NEAR A CRACK

A FUEL METERING SYSTEM FOR DIESEL TRUCKS

January, 1959

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THE ENGINEERING EXPERIMENT STATION

NEEDED: A WIDER LENS

"Indeed, we have long lived in educational isolation and it is time we look around and see what is being done in other countries."–Rear Admiral H. G. Rickover, "European and American Secondary Schools," *Vital Speeches*, Sept. 1, 1958.

THREE RECENT ISSUES of *Current History* were devoted to discussions of the Russian, British, and French educational systems. The editor of the *Indian Concrete Journal* has stated that "the type of education which the engineer receives in this country [India] tends to produce "a trained rather than an educated person," who is not prepared for higher administrative positions. *The Student Engineer*, of Canterbury University College, Christchurch, New Zealand, frequently discusses the value of the humanities, and its prize-winning essay of 1957 dealt with the unfortunate gap between engineers and graduates of the arts colleges. The Hungarian technical journal, *Periodica Polytechnica*, last year published the results of a study of research facilities in six foreign countries. The Dutch and Swiss are contemplating radical curricular changes. Some of our graduate engineers returning from foreign study report that, in education and training, they were one to two years behind graduates of foreign universities. In view of this universal ferment can we afford to heed a voice which adjures us that "the U.S. has not reached its present position by pursuing a policy of copying other nations so let's continue to do our own thinking"?[1] If the writer means to imply that in our thinking we should disregard what is occurring in other parts of the world, we might retort, "Perhaps that's what's the matter with us!"

Fortunately, we have never been so self-critical. At one time we amazed the world with our idea of mass education, though accepting as its price a lower general level than that attained in the selected groups abroad. Now we are faced with the fact that other nations are on the way to achieving a general level exceeding ours, with provision made for selected superior groups, as well. Let us note a few significant movements.

Great Britain. Four of the rapidly growing "local" technical colleges which offer both full-time and part-time courses are increasing the supply of technicians. It is possible for some graduates even to qualify for membership in the Institution of Electrical Engineers.[2]

Keen interest has been expressed by a British engineering journal in Krushchev's proposed revision of the Russian secondary school program. This would provide for seven to eight years of schooling (instead of the present ten), followed by two years of full or part-time productive factory or farm work. At the end of this period, students, then 14 to 15 years old, will be "screened" for qualification to proceed with University or trade-school training. The British "screening" process takes place at eleven years of age. A screening point after "the young person has acquired the self-confidence and broader vision which a working life imparts," the British writer suggests, would lessen the social gap between the accepted and the rejected.

Other advantages of the Soviet system in the eyes of the British are (1) saving in teachers, (2) increase of productive man-hours available to industry, (3) saving of time and energy "wasted on educating the mass of people beyond the stage at which it ceases to be worthwhile for the State," and (4) extending the system of night schools.[3]

It should give us in the United States small comfort to learn that the general standard of spelling and writing of pupils in the English public schools* is "far lower than could be expected," and that chemistry examinations showed "faulty English, lack of precision, ridiculous diagrams and the careless failure to answer the question set."[3] This criticism is based on the British standard. A comparison in arithmetic achievement of some 3,000 11-year-olds in England with a similar sample in California showed a two-to-one superiority of the English pupils.[4]

Nor do the problems arising from the new and expanding branches of science lack attention. A member of the U.K. Atomic Energy Authority, in expressing his own private views, suggests that part of the solution might lie in transferring some of the new science instruction to the lower levels, i.e., the grammar schools.[5]

France. To be admitted to a French university, the lycée graduate must have completed the equivalent of our college freshman and sophomore years.[6] "The master in a lycée has a two-fold mission: first, to keep his mind on the look-out for potential greatness; and secondly, to stimulate among his pupils . . . [a] vigorous intellectual competition." Although the French system has been imitated by most European countries (including Russia), it is now being drastically reformed "along American lines," its objectives being more democracy and more training in science and technology.[6] As a first step the rigid pre-entrance examinations for the lycées have been abolished.

Last November, the science students at the Sorbonne staged a general walkout, and a strike of all students in all the universities in France was called, in protest at the inadequate funds allocated by the government. In one required mathematics course at the Sorbonne, 1400 students tried to get into a lecture room seating 345. This was prior to the announcement that, while denying an increase for education, the government was appropriating an extra 1½ billion francs for building a motorists' tunnel under Mont Blanc.[7]

Russia. Some of us might have been spared our shock at the amazing progress of education in Russia had we known more of its history. Professor Emeritus Timoshenko, in describing education in Russia from 1888, has pointed out that at the beginning of the 20th century Russian universities and engineering schools were on a level with the best of their kind in Western Europe. Requirements were stiff, and competitive examinations determined eligibility for higher education.[8]

The latest proposed revision of the Russian system has already been discussed as a British writer views it. But, for some time, Soviet officials were reported as criticizing their own system. First, the harsh and demanding program sometimes resulted in nervous breakdown and loss of morale in the students. Second, students needed to receive more individual attention. The work program, which does double duty as a preliminary leveler of social rank and a provider of needed farm and factory labor, was also a concession to the fact that the State cannot provide top-level jobs for all of its present graduates.

Professor Leon Trilling, in describing aeronautical engineering education in the USSR, mentioned that, although text books, equipment, and teacher quality were first class, a student entering the laboratory found his equipment all set up, and had only to observe and record the data.[9] However, this weakness may be offset by other means. In Leningrad Polytechnic Institute, practical experience in steel plants is a requirement for graduation, and preference for entrance is given to boys who have worked for two years in an industrial plant (and who have, of course, passed the stiff entrance examinations).[10]

Western Germany. The German system, viewed as among the most successful in the late 19th and early 20th centuries,

(Continued on page 24)

* The British private schools. They are supposed to represent the highest level in British secondary education.

Student in Ceramic Engineering drawing samples from the 3000° F oil-fired furnace.

THE ENGINEERING EXPERIMENT STATION announces the availability of research assistantships for 1959-60. Research opportunities are offered in all branches of engineering, including nuclear engineering.

For consideration as a research assistant, an applicant must have a superior academic record and full graduate standing in the University, and must be prepared to devote half his time to research leading to a thesis. Assignments are open in connection with government- and industry-sponsored projects as well as Engineering Experiment Station projects.

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View of the Structural Research Laboratory showing bending test of a highway bridge plate girder in the 2,400,000-pound testing machine. The girder has a span of 56 feet and is 73 inches deep. This project is sponsored jointly by the U.S. Bureau of Public Roads, and the Washington State Highway Department. Dr. Desi D. Vasarhelyi, of the Civil Engineering Department, is supervisor of the project.

NOTICE!*

The mailing list of THE TREND IN ENGINEERING has assumed such proportions that we must again revise it so as to keep within our limited budget. *If you wish your name to be retained on the list*, please fill out the attached card and drop it in the mail. Deadline to receive cards from points in the U. S. is March 1, 1959.

Note to our Foreign Readers

If you do not live in the United States, Hawaii, or Alaska, it will be necessary for you to enclose the card in an envelope and attach postage. Deadline for receipt of notices from foreign countries is April 1, 1959.

**This notice does not apply to libraries or exchange publications.*

THE TREND IN STRUCTURAL ANALYSIS

ELLIS H. DILL
Assistant Professor of Aeronautical Engineering

E. H. Dill

Two factors are responsible for the rapid progress in analysis in the last ten years, which has equaled that of the preceding one hundred years. First, the extremely complicated structure used in post-World War II aircraft could not be treated efficiently by any of the existing techniques; second, the electronic digital computer has become available to the structural engineer as a practical tool.

Prior to the development of the electronic digital computer, the solution of large sets of simultaneous equations involved great practical difficulties. As a result, structural engineers developed many special techniques each of which proved to be advantageous for a certain narrow class of problems but highly unsuited for problems outside of that class. A treatment of the classical methods and an interesting historical sketch is presented in Reference (1).

The desirable characteristics of a method of structural analysis must now be reconsidered from the point of view of effective use of the electronic computer. In the past the need for arithmetical simplicity necessitated the adoption of many special tools; the full advantage of the digital computer is realized only by the introduction of general methods which can be applied to every problem in structural analysis in exactly the same manner. In this way, the electronic computer can be used to *formulate* the equations as well as to solve them. The use of matrix notation to describe the formulation and the solution of the governing set of equations becomes mandatory. Moreover, matrix notation allows a clear and elegant description of the method and makes possible the derivation of relationships very difficult to perceive without this notation.

The General Method

Let us assume that the form of a structure (building, bridge, airplane, etc.) is given, together with the loads which it must support. It is the job of the structural analyst to determine what proportion of the load is resisted by each component of the structure. In order to accomplish this purpose, the real structure must be idealized into a form susceptible to mathematical treatment. In a bridge we may often idealize the structure as a truss constructed of pin-jointed axial force members and describe these members as elastic lines. In buildings one can generally reduce the primary structure to an assemblage of beams and columns pictured as elastic lines joined at certain end points. In general, the structure will consist of interconnected elastic lines and elastic surfaces. The entire structure is traversed by a grid-work of lines whose intersection points we call node points. We then assume that the elastic surfaces and elastic lines are connected only at these node points. For continuous surfaces (plates and shells), this procedure is similar to the finite difference procedure. The idealization of a complicated wing structure and the break-down into structural elements is illustrated in Fig. 1. The behavior of each basic unit or element of the structure is described by certain forces and moments $\{S\}$ and associated displacements $\{v\}$.* From investigations in the realm of strength of materials and the theory of elasticity, we obtain the

*The brackets $\{\ldots\}$ denote a column matrix. The square brackets $[\ldots]$ will be used to denote the general matrix.

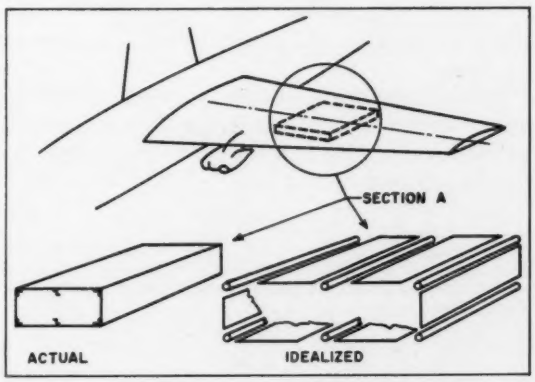

FIG. 1. TYPICAL IDEALIZATION OF WING STRUCTURE

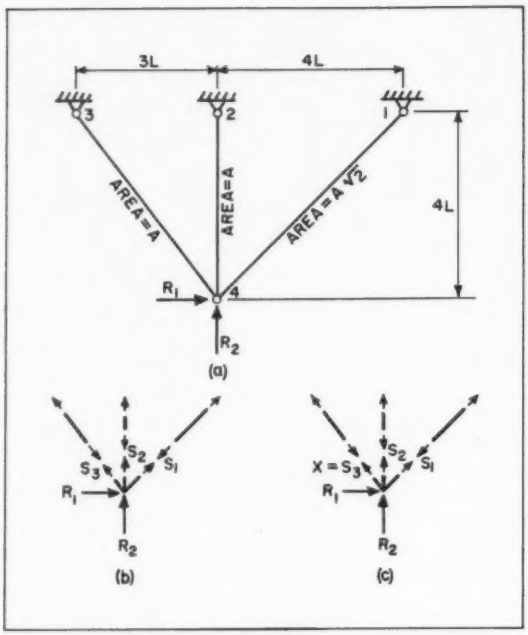

FIG. 2. TRUSS ANALYSIS
(a) Truss dimensions, (b) Internal forces, (c) Choice of redundants in the force method.

force-deformation relations for each element in the form,*

$$\left.\begin{aligned} \{S\} &= [k]\{v\}\,, \\ \{v\} &= [f]\{S\}\,. \end{aligned}\right\} \quad \text{or} \qquad (1)$$

A perfect example is the slope-deflection relations for beams.

At each node, the applied forces must be in equilibrium with the internal forces. Consequently, we have the *equilibrium requirements*,

$$[B]\{S\}+\{R\}=0\,, \qquad (2)$$

where $\{R\}$ denotes the matrix of forces applied at the nodes.

We also have the geometrical requirement of continuity at the joints. That is, the displacements of all elements meeting at a certain node are given by the displacement of that node:

$$\{v\}=[a]\{r\}\,, \qquad (3)$$

where $\{r\}$ denotes the displacements of the nodes in the directions of the forces $\{R\}$. These relations may be called the *compatibility relations*.

In order to clarify these ideas, let us consider a simple example. For the truss of Fig. 2, the elements are described by the bar forces S_1, S_2, and S_3, and by the change in length of each member v_1, v_2, and v_3. The applied forces at Node 4 are R_1 and R_2, and the displacements of that node in the direction of R_1 and R_2 will be denoted by r_1 and r_2, respectively. Considering the freebody of Node 4, we find the *equilibrium equations* by equating the sum of the vertical forces and the sum of the horizontal forces to zero:

$$\left.\begin{aligned} R_1+0.707\,S_1-0.600\,S_3&=0\,, \\ R_2+0.707\,S_1+S_2+0.800\,S_3&=0\,, \end{aligned}\right\} \qquad (4)$$

or,

$$\begin{bmatrix} 0.707 & 0 & -0.600 \\ 0.707 & 1 & 0.800 \end{bmatrix}\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \end{Bmatrix}+\begin{Bmatrix} R_1 \\ R_2 \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \end{Bmatrix},$$

so that

$$[B]=\begin{bmatrix} 0.707 & 0 & -0.600 \\ 0.707 & 1 & 0.800 \end{bmatrix}.$$

The change in length of each member can be expressed in terms of the deflection of Node 4:

$$\left.\begin{aligned} v_1&=0.707r_1+0.707r_2\,, \\ v_2&=r_2\,, \\ v_3&=-0.600r_1+0.800r_2\,, \end{aligned}\right\}$$

or,

$$\begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix}=\begin{bmatrix} 0.707 & 0.707 \\ 0 & 1 \\ -0.600 & 0.800 \end{bmatrix}\begin{Bmatrix} r_1 \\ r_2 \end{Bmatrix}. \qquad (5)$$

Therefore,

$$[a]=\begin{bmatrix} 0.707 & 0.707 \\ 0 & 1 \\ -0.600 & 0.800 \end{bmatrix}.$$

The force-deformation relations for truss members take the form,

$$\left.\begin{aligned} v_1&=\frac{S_1L_1}{A_1E}=\frac{4L}{AE}\,S_1\,, \\ v_2&=\frac{4L}{AE}\,S_2\,, \\ v_3&=\frac{5L}{AE}\,S_3\,, \end{aligned}\right\}$$

or,

$$\begin{Bmatrix} v_1 \\ v_2 \\ v_3 \end{Bmatrix}=\begin{bmatrix} \frac{4L}{AE} & 0 & 0 \\ 0 & \frac{4L}{AE} & 0 \\ 0 & 0 & \frac{5L}{AE} \end{bmatrix}\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \end{Bmatrix}. \qquad (6)$$

*We assume that all forces are applied at node points. In some cases it is desirable to include the possibility of loading on the element itself, as in the case of distributed loads. Then we will have

$$\left.\begin{aligned} \{S\} &= \{S_0\}+[k]\{v\}\,, \\ \{v\} &= \{v_0\}+[f]\{S\}\,, \end{aligned}\right\} \quad \text{or}$$

where $\{S_0\}$ and $\{v_0\}$ are initial loads or deformations, such as the fixed end moments in the slope-deflection equations for beams.

Therefore,

$$[f]=\begin{bmatrix} \frac{4L}{AE} & 0 & 0 \\ 0 & \frac{4L}{AE} & 0 \\ 0 & 0 & \frac{5L}{AE} \end{bmatrix}.$$

The result is the general formulation of the problem, involving eight equations in the eight unknowns: S_1, S_2, S_3, v_1, v_2, v_3, r_1, r_2. The applied forces are assumed to be given. In this example, the equations of equilibrium at Nodes 1, 2, and 3 have not been written. However, a complete statement of the problem must include those conditions in the general case, since they are necessary in order to find the reactions.

The solution of any problem in structural analysis is always reducible to the solution of the linear algebraic set of Eqs. 1, 2, 3.* Hence we conclude that in principle the analysis of intricate elastic systems involves only very simple mathematical and physical ideas. Equations 2 and 3 are easy to formulate for any structure; thus, the central problem really is the prior determination of the force-deformation relations, Eq. 1. In the case of framed structures, the force-deformation relations are given by the usual slope-deflection equations as presented in Reference (1). In the case of flat sheets the relations are given in Reference (2). Other structural elements are treated in Reference (3). The formulation of Eqs. 1, 2, and 3 for some complex structures is presented in Reference (4). Since this general formulation of the problem leads to a large number of simultaneous equations, it is sometimes desirable to use an approach which allows an indirect formulation of Eqs. 2 and 3 and reduces the number of equations treated at any one step. Two general lines of attack are available: the force method and the displacement method.

The Force Method

Having formulated the equilibrium conditions (Eq. 2), we find that certain problems which have received much study in the past become trivial. In particular, the concept of static determinacy simply becomes a question of whether there are as many equations in (2) as there are unknowns $\{S\}$; i.e., is $[B]$ a square matrix? In this case, by using only Eqs. 2, one can solve for the internal forces, i.e., find the inverse of $[B]$. The previously troublesome problem concerning the possibility of a critical configuration in statically determinate trusses is answered by considering the determinant of $[B]$. If the determinant is zero, then the inverse of $[B]$ does not exist and the configuration is unstable.

In general, there will be n equations but m unknowns ($m>n$). In this case the problem is termed statically indeterminate. The force method consists of regarding $(m-n)$ of the forces, denoted by $\{X\}$, as unknown applied forces which are to be determined from the requirement of compatible deformations.† We can write from Eq. 2:

$$\{S\}=[b_0]\{R\}+[b_1]\{X\}\,. \tag{7}$$

From the compatibility equations (3), which then contain m deformations $\{v\}$ and n node displacements $\{r\}$, we eliminate the node displacements to obtain

$$[c]\{v\}=\{0\}\,, \tag{8}$$

and, since

$$\{v\}=[f]\{S\}\,,$$

we have‡

$$[c]'[f][b_0]\{R\}+[c]'[f][b_1]\{X\}=\{0\}\,.$$

We then can solve for $\{X\}$, and hence obtain the value of $\{S\}$.

In our example we have

$$\left.\begin{aligned} S_1&=-\sqrt{2}R_1+(3\sqrt{2}/5)X\,,\\ S_2&=R_1-R_2-(7/5)X\,,\\ S_3&=X\,, \end{aligned}\right\}$$

or,

$$\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \end{Bmatrix}=\begin{bmatrix} -\sqrt{2} & 0 \\ 1 & -1 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} R_1 \\ R_2 \end{Bmatrix}+\begin{bmatrix} 3\sqrt{2}/5 \\ -7/5 \\ 1 \end{bmatrix}\{X\}\,, \tag{9}$$

and from Eq. 5,

$$(3\sqrt{2}/5)v_1-(7/5)\,v_2+v_3=0\,; \tag{10}$$

therefore,

$$[c]=[3\sqrt{2}/5 \quad -7/5 \quad 1]\,.$$

Hence, using Eq. 6,

$$5X+\frac{12\sqrt{2}}{5}\,S_1-\frac{28}{5}\,S_2=0\,,$$

from which the value of X, etc., can be obtained.

While this derivation of the force method from the fundamental set of Eqs. 1, 2, 3 serves to unify the

*As usual, one could form a parallel statement of the problem in terms of energy principles.

†The treatment here follows Reference (5).

‡The primes $[\ldots]'$ and $\{\ldots\}'$ denote the transpose of the matrix.

concepts, in practice one would attempt to formulate the matrices $[b_0]$, $[b_1]$, and $[c]$ *directly* for any given problem. The usefulness of the force method depends on our ability to formulate these matrices in a simple manner. The matrices $[b_0]$ and $[b_1]$ are easily found by simple statically determinate analysis of a certain base structure for unit loads at each applied load and at each unknown force $\{X\}$ in succession. The unknowns, $\{X\}$, are called redundant forces. The direct formulation of the compatibility relation is somewhat more difficult. As will be shown in the next section, this apparently difficult problem can be overcome quite simply by the application of the principle of virtual forces.

Let us return to the simple example. First, letting $S_3=0$, and solving for S_1 and S_2 from the requirement of equilibrium of Node 4; and second, letting $R_1=0$, $R_2=0$, and $S_3=X$, and solving for S_1 and S_2, we obtain the equilibrium equations in the form of Eq. 9.

The Virtual Work Theorem

The theorem of virtual work is one of the most valuable tools available to the worker in the field of mechanics. In its most general form it may be stated as follows:

Any force system which is in equilibrium does zero work during an arbitrary displacement.

In this statement, the internal forces are considered part of the force system. In order to apply this theorem to problems, one may regard the force system to be the actual force system existing in a body and the displacements to be any suitable set of displacements which deform the body in a continuous manner; these are called virtual displacements. In this case we obtain the virtual displacement law:

The total work done by the external and internal forces during a virtual displacement is zero.

On the other hand, one may regard the displacements to be the actual displacements of the body due to the given loads, and choose the force system to be any arbitrary equilibrium system of external and internal forces which could exist on the given structure. Such a force system is called a virtual force system and the resulting law is called the virtual force law:

A virtual force system does zero work during the displacement of the body.

Application of the first theorem is easily shown to be equivalent to the equations of equilibrium (Eq. 2). Application of this second theorem in its most general form leads to the compatibility relations. Choose as virtual force system that force system consisting of a unit load at one redundant, together with the resulting internal forces, $\{\bar{S}\}$, the other redundants and the applied forces being equal to zero. Imagine the structure to perform the actual displacements $\{v\}$ which would be caused by the external loads acting on the complete structure. The work done by the unit load is therefore equal to the deflection at the redundant force X_1 but, the structure being continuous, we require the deflection at X_1 to be zero. Therefore, the work done by the internal forces $\{\bar{S}\}$ must be zero, or,

$$\{\bar{S}\}'\{v\}=\{0\}\,.$$

Repeating for unit loads at each of the other redundants and observing that the stresses $\{\bar{S}\}$ are given in each case by one column of the matrix $[b_1]$ occurring in Eq. 7, we obtain

$$[b_1]'\{v\}=\{0\}\,. \tag{11}$$

Comparing this relation with Eq. 8, we see that

$$[c]=[b_1]'\,. \tag{12}$$

Hence no additional calculation for $[c]$ is necessary, and the analysis of any structure is reduced to the determination of the Eqs. 7, a simple statically determinate analysis! From Eqs. 9 and 10, then, we see that Eq. 12 holds in the example.

The Deformation Method of Solution.

If Eq. 2 includes the equilibrium equation at all nodes, then we may substitute Eq. 3 into Eq. 1, giving

$$\{S\}=[k]\,[a]\{r\}\,,$$

and this into Eq. 2 gives

$$[B][k][a]\{r\}=-\{R\}\,.$$

If we let

$$[K]=[B][k][a]\,,$$

then,

$$\{r\}=[K]^{-1}\{R\}\,,$$

and, from Eqs. 1 and 3,

$$\{S\}=[k][a]\{R\}\,.$$

Hence the problem is solved.

This process is capable of physical interpretation. The matrix $[K]$ can be formed by direct addition of the stiffness of each element.[2]

In our simple example we have

$$S_1=\frac{AE}{4L}v_1=\frac{AE}{L}\left(\frac{1}{4\sqrt{2}}r_1+\frac{1}{4\sqrt{2}}r_2\right),$$

$$S_2=\frac{AE}{4L}v_2=\frac{AE}{L}\left(\frac{\sqrt{2}}{4}r_2\right),$$

$$S_3=\frac{AE}{L}\left(-\frac{3}{25}r_1+\frac{4}{25}r_2\right),$$

and, from Eq. 4,

$$-R_1=\frac{AE}{L}\left(\frac{1}{8}+\frac{9}{125}\right)r_1+\frac{AE}{L}\left(\frac{1}{8}-\frac{12}{125}\right)r_2,$$

$$-R_2=\frac{AE}{L}\left(\frac{1}{8}-\frac{12}{125}\right)r_1+\frac{AE}{L}\left(\frac{1}{8}+\frac{1}{4}+\frac{16}{125}\right)r_2,$$

etc., or,

$$[k]=\frac{AE}{L}\begin{bmatrix}\frac{1}{4} & 0 & 0\\ 0 & \frac{1}{4} & 0\\ 0 & 0 & \frac{1}{5}\end{bmatrix};\quad [a]=\begin{bmatrix}1/\sqrt{2} & 1/\sqrt{2}\\ 0 & 1\\ -\frac{3}{5} & \frac{4}{5}\end{bmatrix};$$

and

$$[B]=[a]'.$$

The usefulness of the deformation method depends upon our ability to formulate the matrices $[B]$, $[a]$, and $[k]$ in a simple direct manner. This is described in detail in References (2) and (6). One chooses at each node the member displacements to coincide with the nodal displacements. Then the force-deformation relations become

$$\{S\}=[k]\{r\},$$

i.e., the matrix $[a]$ becomes a unit matrix. (The stiffness matrix $[k]$ will contain many zeros since $\{r\}$ represents *all* nodal displacements.)

Then, choosing the member forces to be always either in the X or Y direction, the equilibrium equations become

$$\{S\}_1+\{S\}_2+\{S\}_3+\ldots+\{S\}_n=\{R\},$$

where the subscripts refer to a particular element, and zeros are added to make the matrices compatible.

Using the above force-deformation relation, this becomes

$$[k]_1\{r\}+[k]_2\{r\}+\ldots+[k]_n\{r\}=\{R\},$$

and, therefore,

$$([k]_1+[k]_2+\ldots+[k]_n)\{r\}=\{R\}.$$

Hence,

$$[K]=[k]_1+[k]_2+\ldots+[k]_n.$$

That is, the total stiffness matrix is formed by *simple addition* of the member stiffness matrices after augmenting them by zeros.

Since the deformation method considers displacements as unknowns, it is often used in dynamics problems.

The Classical Methods

All of the classical methods of analysis may be viewed as if they were special ways of formulating Eqs. 1, 2, or 3.

Slope-deflection equation for beams. These equations are precisely the force-deformation equations for beams. The equilibrium equations are formed by equating moments at all joints. The compatibility equations take the form of equality of slopes at each support.

Three-moment theorem. These equations are really the solution to the statically indeterminate problem of a two-span continuous beam. Their use is significant since it represents a special application of the general idea of piecing together not just single elements but whole assemblies of elements for which we have previously obtained a complete solution. This piecing technique will eventually allow complete automation in the analysis of very large building frames.

Moment area principles and elastic weights (conjugate beam). These relations are special forms of the force-deformation relations for beams.

Moment distribution. The method of moment distribution is ultimately an iteration method of solution of the fundamental equations in the case where the force-deformation relations are given by the slope-deflection equations. However, this does not minimize the importance of this great contribution to structural analysis. Although the interest in successive approximation techniques (including relaxation) must necessarily decrease with the advent of the digital computer, these techniques will always remain a quick convenient way to solve fairly complicated problems and therefore can never be discarded completely.

Column Analogy. This method is identical with the method of elastic center.

Elastic center. This method consists of choosing the redundant forces in such a way as to nearly diagonalize the matrix occurring in the compatibility relations and thereby to reduce the work in solving for the redundant forces. It is a special technique applicable only in the case of rigid frames having three or fewer redundants, and is, therefore, hardly worth considering.

One can continue this reasoning for all of the multitude of classical methods.

Conclusions

The solution of statically indeterminate structures, which in the past has been a difficult problem, is today a simple one. Whenever the force-deformation relations are known, especially in the case of beams, frames, and trusses, one has simply to write Eqs. 1, 2, and 3 and turn the resulting matrices over to a computing group for inversion of the matrix. Or, if the resulting set of equations is large, as it will be for a complicated aircraft structure, the force method

(Continued on page 21)

ESTIMATION OF MAXIMUM RUNOFF BY MEANS OF AERIAL PHOTOGRAPHS

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The term "runoff" designates all water that drains from land areas by surface channels into which the water collects from overland flow or subterranean passages. In other words, runoff is the water remaining from precipitation after the losses from evaporation, transpiration, and seepage into the ground. Information about runoff is important in many kinds of engineering projects. It may be the controlling factor in the location of highways, railroads, or airports and is of vital significance in the design of culverts, bridges, storm drains, sewage systems, dams, and other engineering structures. It is a never-ending problem in the maintenance of these facilities.

Empirical runoff formulas are useful for preliminary and comparative estimates when the engineer is not justified in taking the time and expense of making a long, detailed investigation. Time may be a limiting factor in some cases where lack of observation and uncertain available data preclude detailed study, and a rough estimate has to suffice.

The purpose of this paper is to show a way in which the estimation of maximum runoff of a given drainage area can be greatly facilitated by the use of aerial photography, the photographs being used as a source of both interpretation and measurement in providing data that are usually secured by field surveys, maps, charts, and records from such agencies as the U. S. Geological Survey.

One of the better known runoff formulas is one proposed by the Swiss hydraulician, Burkli-Zeigler in 1880. His formula was derived from observations on heavy storms in Switzerland, together with information from other European localities. Numerous observations were tabulated establishing the relationship between the measured runoff at checking points and the drainage areas contributing to the runoff. Two characteristics of the drainage areas in addition to their size were noted: the average slope of the area, expressed in feet per thousand, and an evaluation of a surface coefficient or "imperviousness factor" dependent largely on the type of soil and ground cover. The formula is expressed as follows:

G. K. Saito

$$Q = CRA\sqrt[4]{S/A} \qquad (1)$$

in which,

Q = quantity of water (cfs) reaching the check point,

C = coefficient depending on type of surface drained. Estimated values of C vary from 0.90, for densely built-up municipal areas with paved streets, to 0.10 for densely forested areas with pervious soil.

R = average rainfall during heaviest fall on record (cfs per acre). (One in. of rainfall per hour is closely equal to 1 cfs per acre.) The value of R depends on local rainfall conditions and varies in practice from 0.50 to 2.5, with 0.80 to 1.25 a general average west of the Cascade Mountains in Washington.

A = drainage area (acres.).

S = average slope of ground (ft per 1,000 ft). The slope should be that of the main channel of flow, that is, the channel which determines the time of concentration of runoff for the watershed.

Customary practice has been to obtain the necessary data for use in the various empirical runoff formulas from field surveys supplemented by study of topographic maps. The use of stereo-pairs of aerial photographs as a source of data for the estimation of runoff has not hitherto been reported, to the knowledge of the writers.

* Mr. Saito was a member of Professor Chittenden's class in Photogrammetry which is open to students in Geography, Geology, and Forestry, as well as Civil Engineering.

The use of aerial photographs for runoff estimation becomes significant in the light of the following statements. Any given drainage area is usually covered by one map or another. The problem, however, is whether it is covered by a topographic map of large enough scale to be serviceable. Another consideration is the question of map date. Many topographic maps are far out of date and changes may have occurred since their completion to affect the runoff drastically. Aerial photographs properly interpreted can provide both the appropriate measurements and qualitative information useful in the estimation of runoff more quickly and at a lower cost than maps or field research. They require very simple equipment and only the basic principles of photogrammetry. The necessary equipment consists of a set of photographs covering the drainage area in question, flown on a strip pattern with successive exposures in line of flight overlapping each other by approximately 60 per cent, a mirror stereoscope, and a measuring device such as a parallax ladder which can provide photo-measurements directly to 0.01 in. and, with reasonable estimation, to 0.001 in. with the optical assistance of the stereoscope. The flight altitude of the plane during photography and the focal length of the camera used must be known.

Aerial photographs can be effectively used to supply values for the factors C, A, and S composing the Burkli-Zeigler formula leaving only R to be secured from existing precipitation records for the given locality.

The measurement of the factor A (drainage area) will be considered first. Since the stereoscope brings out the relief of any area common to two overlapping photographs (a photo-pair) in a most striking manner by the visual creation of a relief model of the overlap with greatly exaggerated vertical scale, it is not difficult to delineate the drainage area in question. In areas of low or moderate relief, the tracing of the drainage boundary can be quite difficult on a topographic map since the contours would be quite wide apart. The vertical exaggeration under the stereoscope makes easier the tracing of the divide in such areas. After the drainage boundary delineation, which often involves many photographs, the usual procedure is to arrange them in the form of a photomosaic and to measure the area with a planimeter and reduce it to acres.

In determining the slope factor S, the location of both the checking point and the head of drainage are plotted on the photographs. Those photographs are then properly mounted by stereo-pairs so that parallax measurements can be determined, using the stereoscope and the parallax ladder and working with as many successive stereo-pairs as may be necessary to span the distance between the head of drainage and the checking point. The difference in elevation between any two points appearing within the overlapped portion of a stereo-pair is determined by use of the principle of differential parallax, employing the basic parallax equation:

$$\Delta h = \frac{(H - h_a)\,(D_a - D_b)}{(D - D_b)}, \qquad (2)$$

where

Δh = difference in elevation between a point "a" and a point "b" (ft),
H = flight altitude of plane above mean sea level (ft),
h_a = assumed or mean sea-level elevation of a point of known elevation (ft),
D_a = parallax measurement between the images of point "a" as seen on each photograph of the stereo-pair (in. or mm),
D_b = parallax measurement between the images of point "b" as seen on each photograph of the stereo-pair (in. or mm),
D = separation between the principal points of the stereo-pair as mounted for stereoscopic viewing (in. or mm).

The terms of this formula are based upon direct linear measurements taken from a properly mounted stereo-pair combined with certain data commonly set by the particular flight plan under which the photographs were taken. By using this formula, if the elevation of one point is known, the elevation of another point in the same overlap area can be determined. Since the checking point and the point selected as the head of drainage are not usually close enough together to fall on the overlap of a single stereo-pair, the parallax formula must be applied to as many overlap areas of as many stereo-pairs as are necessary in order to extend the difference in elevation between the terminal points in question. The distance between the terminal points is secured as a direct linear measurement following the main collection channel from the head of drainage to the checking point and is converted into feet by applying the average scale of the photographs. Dividing the difference in elevation by the distance between terminal points and multiplying by 1000 yields the desired slope factor, S.

The surface coefficient factor, C, presents an opportunity for the use of aerial photographs in a very important but purely interpretational sense. Up to the present time, to the writers' knowledge, the evaluation of the C factor in the Burkli-Zeigler formula has been determined largely by identification of the observed surface characteristics of a given area with a word description found in a table of

PHOTOMOSAIC SHOWING THE DRAINAGE AREA OF THE NORTH

HE NORTH FORK OF MERCER CREEK ABOVE THE GAGING STATION

surface coefficients. Many such tables have been produced and are an important part of the literature on runoff. A typical example, taken from Hickerson's *Route Location and Surveying*, "Drainage Surveys and Facilities for Storm Sewer and Culvert Design," gives the following C values:

Densely built up municipal areas with paved streets	0.75-0.90
Densely populated residential areas with paved streets	0.50-0.80
Suburban areas with large lots, surfaced roads	0.30-0.60
Timberland, depending on density	0.25-0.50
Parks, meadows, rural areas, depending on character of subsoil	0.10-0.30

In this aspect of the work of estimating runoff, a photo-interpretation key to replace or supplement the descriptions given in such a table would be most useful to the engineer for rapid and accurate identification of the appropriate C factor applying to a given area. To be sure, surface conditions will rarely be uniform over an entire drainage area, but the areas of different surface conditions can be observed and weighted as to their percentage of the entire area to determine an average value for C.

To give practical application to the ideas thus far expressed, a test field problem was recently completed embracing the watershed of the North Fork of Mercer Creek located approximately four miles southeast of Kirkland, Washington. This area was selected as being typical of the suburban-rural areas of King County and also because the U. S. Geological Survey maintains a gaging station at the checking point and has records of discharge running back for several years. Moreover, complete photo-coverage at a satisfactory scale was available from Pacific Aerial Surveys. (See accompanying illustration.)

Materials and Equipment:

Photographs: 5-13 to 5-18 inclusive.
(The drainage area in question being long in comparison with its width was satisfactorily covered with a single strip flight of 6 overlapping photographs.)

Average scale of photographs: 1:12,000 or 1 in.= 1,000 ft.

Focal length of camera lens: 12 in.

Elevation of checking point "A" (see photo S56-5-17): 175 ft.

Recorded rainfall: 0.15 in. over 5-min period (U. S. Weather Bureau). The drainage area used in this problem has been gaged by the USGS Water Resources Division at 241 cfs as an instantaneous figure and not the maximum average over an hour's duration as required in the Burkli-Zeigler formula. The value of 0.15 in. has been adopted as the best maximum value available on record. This value multiplied by 12, to obtain a rainfall figure extending over an hour's duration, = 1.80 in., which has been accepted as the R factor in this problem.

Altitude of flight: 12,340 ft.

Procedure:

1. Viewing the photographs stereoscopically, the watershed contributing to the runoff checking point "A" was delineated.
2. The area of the watershed was determined by arranging the photographs into a photo-mosaic and measuring the delineated area with a planimeter. Reduced, "A" was found to equal 1311 acres.
3. By application of the previously mentioned basic parallax formula, using suitable measurements on successive pairs of photographs, the difference in elevation between the checking point, "A," and the head of drainage point, "B," was secured. (See photo S56-5-14.) This difference, applied to the photo-scale distance between points "A" and "B" and reduced to feet/1000 gave the slope factor S for the runoff formula. For this problem S=25.6 ft/1000 ft.
4. In selecting the surface factor C, two categories were considered:
   a) Wooded area (of mixed evergreen and deciduous growth), composing about ⅔ of the drainage area, was assigned a value of 0.30.
   b) Farmland, pastures, and suburban residential area, composing the remaining ⅓ of the drainage area, was assigned a value of 0.25.

   The average value of $C=\frac{2}{3}(0.30)+\frac{1}{3}(0.25)=0.283$.
5. Applying these values to the Burkli-Zeigler formula yields a value for Q of 249.5 cfs, a figure comparing quite favorably with the recorded figure of 241 cfs as determined by the U. S. Geological Survey.

This paper has been presented in the hope of stimulating interest in an application of aerial photography which may offer possibilities of considerable usefulness. Considering only those factors in the runoff formula for which aerial photographs may be utilized, it is apparent that the runoff coefficient, C, is the most difficult to evaluate. A great deal of correlative study is obviously required to produce a photo-interpretation key useful for a given locality. Experience in photo-interpretation and a knowledge of the geology of the region would be helpful if not essential. The A and S factors are largely quantitative and are comparatively easy to evaluate by definite measurements on the photographs.

A Photoelastic Study of Strain-Energy Storage Near a Crack

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THE STUDY OF CRACK PROPAGATION in structural materials has become a matter of great importance, as emphasized by unexpected accidents to aircraft, ships, and land-based structures, where the rapid spread of cracks was disastrous. Among the many factors involved in crack propagation is the storage of strain energy near a crack, since the spreading of a crack can be abetted by the release of strain energy from adjacent material.

In connection with familiarization studies being conducted in the use of the newer photoelastic techniques, such as fringe multiplication, an endeavor to check experimentally some analytically determined values of strain-energy storage near a crack in sheet material under tension seemed worth consideration. The present article is a report of an exploratory study toward this end.

The specimen chosen for investigation was a strip of CR-39 plastic (Columbia resin) 0.125 in. thick, 1.50 in. wide, and 18 in. long, loaded in longitudinal tension with a length of 15 in. between the loading grips. A transverse central crack was simulated with a saw-cut 0.50 in. long, made with a $\frac{1}{48}$ in. jeweler's saw, starting from a $\frac{5}{32}$-in. central hole. A grid of $\frac{1}{8}$-in. squares was scratched on the specimen, as shown in Fig. 1.

The direct purpose of the photoelastic investigation was to determine the excess amount of strain energy stored in the gridded portion of the specimen, as compared to an identical uncracked specimen subjected to the same longitudinal load, and to compare this excess amount of strain energy with analytically determined values of the same quantity.

At this point, it may be well to note the engineering significance of the strain-energy excess to be evaluated, in that it is closely related to the strain energy that is released when a crack forms in a stressed specimen whose ends are rigidly fixed during crack propagation.

For the first part of the photoelastic study, a constant longitudinal load of 87 lb was applied to the specimen, corresponding to an average stress of 464 psi over the gross cross section, or 696 psi average over the net cross section at the crack. Because of the stress concentration caused by the crack (saw-cut), and because of the brittleness of the CR-39 plastic, the specimen would have broken before the load could be raised to a value that would produce enough photoelastic fringe orders to permit a satisfactory analysis to be made by conventional photoelasticity. Therefore, to provide a considerable number of fringe orders under a load low enough to avoid danger of fracture, resort was taken to Post's method of fringe multiplication,[1] using a fringe-multiplication factor of 9. A drawing of the resulting isochromatic fringe pattern is shown in Fig. 2, where the material had a photoelastic fringe constant of 75 lb per inch per order. (The area shown in Fig. 2 is the gridded area indicated in Fig. 1.) The decimal value of fringe order at the center of each square in the gridded section was determined and was converted to the equivalent fringe order that would have existed if the longitudinal load had been 1000 lb and if there had been no fringe multiplication. Table I lists the equivalent fringe order at the center of each square, with positions in this table corresponding to the positions of the squares in the grid shown in Fig. 1.

To supplement the isochromatic fringe pattern, an isoclinic fringe pattern was next obtained by conventional photoelastic methods, as shown in Fig. 3. Transverse principal-stress trajectories through selected points were then determined, as shown in Fig. 4. Filon's method of graphical integration [2,3] was utilized to determine the individual principal stresses at the center of each square in the gridded area. Table II lists one principal stress at the center of each square in the grid, and Table III lists the other principal stress at each corresponding point.

At any given point in the specimen, assuming plane stress, the strain energy per unit volume is $(1/2E)(\sigma_1^2+\sigma_2^2-2\mu\sigma_1\sigma_2)$, where E is Young's modulus, μ is Poisson's ratio, and σ_1 and σ_2 are the principal stresses. Therefore, if it be assumed that the stress-strain conditions are uniform throughout each square in the grid, the total strain energy stored in the gridded section of the specimen can be calculated from the data in Tables II and III, plus a knowledge of Poisson's ratio for the material, which was taken to be 0.35.

* Mr. Cheng, who received his degree of M.S. in M.E. at the University of Washington in 1957, is working toward his Ph.D. at the Illinois Institute of Technology.

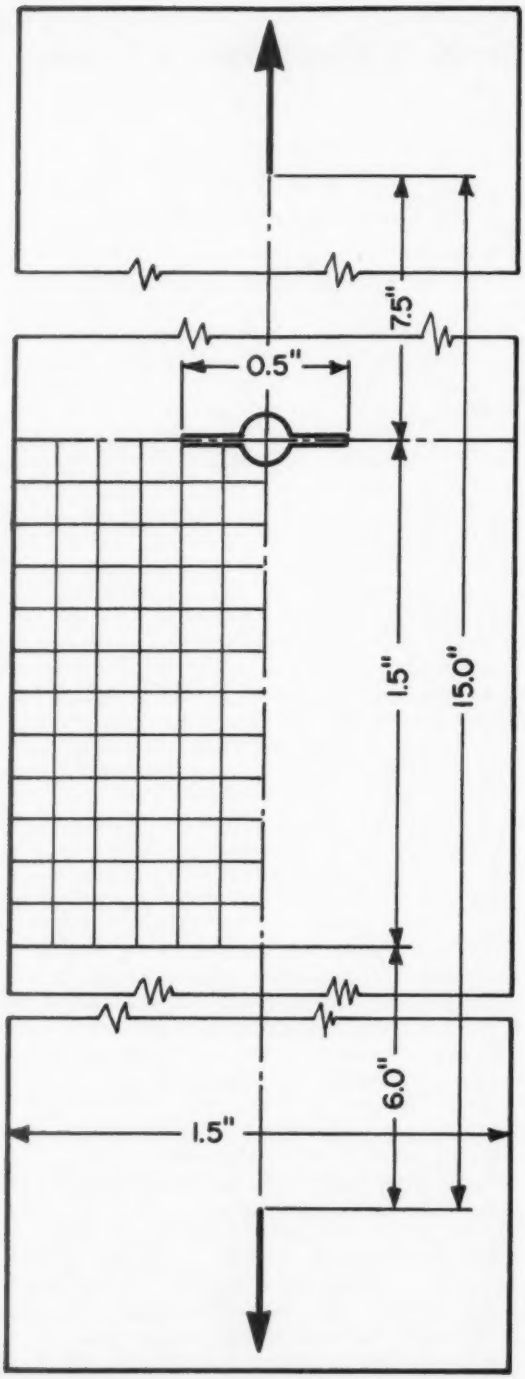

FIG. 1. DIAGRAM OF TEST SPECIMEN SHOWING GRIDDED AREA

TABLE I

EQUIVALENT ISOCHROMATIC FRINGE ORDERS FOR 1000-LB LOAD AND NO FRINGE MULTIPLICATION*

8.93	8.93	8.93	14.30	6.66	....
9.28	10.46	12.50	15.40	8.96	5.36
10.46	10.72	11.78	11.78	8.96	5.36
10.72	10.72	10.72	10.24	8.40	5.36
10.72	10.46	9.27	9.78	7.43	6.21
10.46	9.97	9.78	9.40	7.43	6.65
9.97	9.78	9.25	8.30	7.43	6.96
9.85	9.52	8.93	8.30	7.68	7.15
9.78	9.25	8.82	8.30	7.88	7.53
9.52	8.96	8.72	8.30	8.12	7.88
9.52	8.96	8.72	8.40	8.30	8.12
9.52	9.96	8.72	8.50	8.40	8.40

* Values apply to the centerpoint of each grid-square.

TABLE II

EQUIVALENT MINOR PRINCIPAL STRESSES*
(Psi for 1000-lb load)

45	402	1445	1990	−2821	−2310†
34	60	−160	−1128	−1341	−1993
−43	−123	−583	−1047	−1378	−1146
−54	−190	−489	−759	−569	−251
0	−89	−239	−315	−151	42
0	−57	−81	−23	−23	171
0	−17	−14	63	158	268
0	15	53	191	193	301
0	34	114	114	181	239
0	51	121	151	252	271
0	36	89	89	89	127
0	0	0	0	0	0

* Tensile stress indicated positive.
† Value obtained by interpolation.

TABLE III

EQUIVALENT MAJOR PRINCIPAL STRESSES*
(Psi for 1000-lb load)

5403	5760	6803	10570	1175	980†
5602	6336	7340	8112	4035	1223
6233	6309	6485	6021	3998	1854
6378	6242	5943	5385	4471	2965
6432	6187	5743	5553	4307	3318
6276	5925	5787	5071	4435	4161
5982	5851	5536	5043	4616	4444
5910	5727	5411	5171	4801	4591
5868	5584	5406	5094	4909	4757
5712	5427	5353	5131	5124	4999
5712	5412	5321	5129	5069	4999
5712	5376	5232	5100	5040	5040

* All these stresses are tensile.
† Value obtained by interpolation.

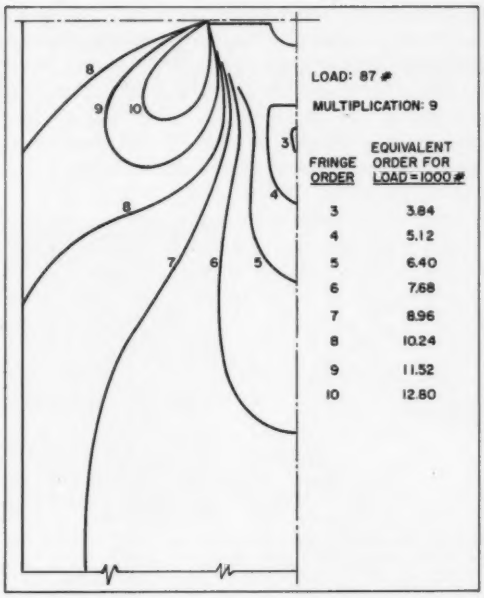

FIG. 2. ISOCHROMATIC FRINGE PATTERN

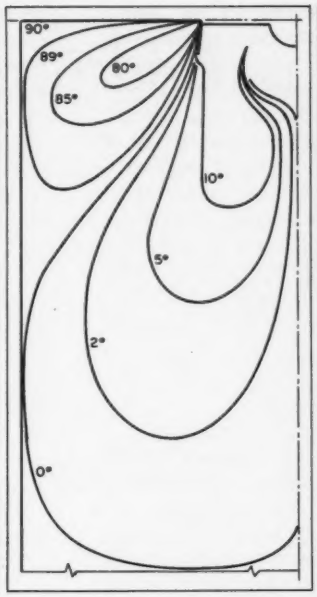

FIG. 3. ISOCLINIC FRINGE PATTERN

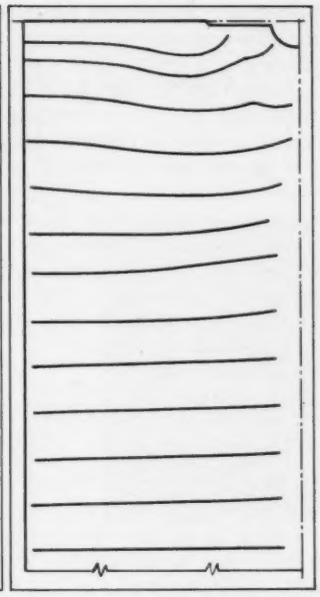

FIG. 4. TRAJECTORIES OF TRANSVERSE PRINCIPAL STRESS

The sum of the squares of all the principal stresses listed in Table II was found to be 33×10^6, and the corresponding value for Table III was 2138×10^6. The sum of the $-2\mu\sigma_1\sigma_2$ values was 6×10^6. The grand total of these three summations was 2177×10^6. Multiplying this figure by $1/2E$ and then by the volume of material corresponding to one square in the gridded section gives the total strain energy stored in the gridded section of the specimen. The resulting value of stored strain energy is $(1/2E)(4.25 \times 10^6)$ in-lb for the cracked specimen under a simulated longitudinal load of 1000 lb.

If there had been no crack (saw-cut) in the specimen, the 1000-lb simulated longitudinal load would have produced a uniform longitudinal tensile stress of 5330 psi and no transverse stress. The total strain energy stored in the gridded section would then have been $(V/2E)(5330^2)$, where V is the volume of the gridded section, which is 0.1406 cu in. From this calculation, the total strain energy stored in the gridded section of the specimen, in the absence of a crack, would have been $(1/2E)(3.99 \times 10^6)$ in-lb for a simulated longitudinal load of 1000 lb.

From the preceding two paragraphs it may be seen that the strain energy stored in the gridded section of the cracked specimen is greater than if there were no crack by the amount of $(1/2E)(4.25\text{–}3.99)(10^6)$, or, $(1/2E)(0.26 \times 10^6)$ in-lb, which is an increase of 7 per cent over an identical uncracked specimen under the same longitudinal load.

In order to provide a comparison with this photoelastically determined value of strain-energy storage, the theoretical analyses of Griffith, Irwin, and Greenspan were utilized. Apparently the first to calculate the strain-energy relationships around a crack was A. A. Griffith,[4,5] who based his analysis on a calculation of stress distribution near a crack by C. E. Inglis.[6] In Reference (5), Griffith corrected an error in the strain-energy equation that he had published in Reference (4) and concluded that if a transverse central crack forms in a very wide sheet under constant longitudinal tensile load, the strain energy stored in the material increases by the amount, $\pi c^2 t\sigma^2/E$, where c is half the length of the crack, t is the thickness of the sheet, σ is the longitudinal stress in the absence of the crack, and E is Young's modulus of the material. This expression can be rearranged to $(\sigma^2/2E)(2\pi c^2 t)$, which is recognizable as the product of the strain energy per unit volume in the uncracked sheet, times the volume of an elliptical portion of the sheet whose minor axis is the crack and whose major axis is twice the length of the crack. Evaluating this last expression for the present specimen, under 1000-lb load, gives $(5330^2/2E)(6.28)(0.25^2)(0.125) = (1/2E)(1.394 \times 10^6)$ in-lb of strain energy stored in the specimen because of the presence of the crack. This stored strain energy amounts to an excess of 8.7 per cent over the strain energy stored in the gridded section of an uncracked specimen under the same load,

taking into account the fact that the gridded section includes only one quadrant of the area surrounding the crack.

Since Griffith's analysis was derived for a very wide sheet (i.e., for a vanishingly small ratio of crack length to sheet width), an additional comparison of the photoelastically determined strain energy was made with an analysis by Greenspan[7] which takes into account the ratio of the crack length to the sheet width. Greenspan derived an expression for the effect of holes on the longitudinal stiffness of a sheet under tensile load, and Irwin[8] has rearranged Greenspan's expression to apply it to a sheet with a transverse central crack, as follows:

$$K=\frac{2-y^2-y^4}{2+(r-1)y^2-y^4}$$

where K is the ratio of stiffness of the cracked sheet to the stiffness of the uncracked sheet, y is the ratio of the crack length to the sheet width (which is $\frac{1}{3}$ for the present specimen), and r is π times the width-length ratio for the length of specimen being considered. (The value of r is 1.57 for the gridded section of the present specimen.) Evaluating this expression for the present specimen gives $K=0.915$. That is, the longitudinal stiffness of the gridded section of the cracked specimen is calculated to be 0.915 times the stiffness of the same section in the absence of the crack. For any two elastic members under the same longitudinal load, the stored strain energy is inversely proportional to the stiffnesses of the respective members. Therefore, the strain energy stored in the gridded section of the cracked member is equal to the corresponding value in the absence of the crack, times $1/K$, where $1/K$ for the present specimen is 1.092. Thus, using Greenspan's analysis, the strain energy stored in the gridded section of the cracked specimen is calculated to be 9.2 per cent greater than if the specimen were subjected to the same load in the absence of a crack.

Summarizing, it was found that the presence of a transverse central crack (saw-cut) in the test specimen caused a percentage increase of stored strain energy within the gridded section shown in Fig. 1, under a simulated 1000-lb longitudinal tensile load, as follows:

Photoelastic analysis	7%
Theoretical analysis (Griffith)	8.7%
Theoretical analysis (Greenspan, Irwin)	9.2%

Considering the complexity involved in the photoelastic analysis, this check with theoretical analyses is considered rather good. A perfect check would not be expected since all three analyses involved approximations as applied to the test specimen used. In the photoelastic analysis, the strain-energy storage was assumed uniform within each square of the gridded section of the specimen, and other approximations were necessary in applying the experimental observations. Presumably a little of the excess strain energy resulting from the crack was stored outside the portion of the specimen of which the gridded section was a quadrant, so that the calculated percentage of excess strain energy would be expected to be a little low. The Griffith analysis is inexact for the present application, because it applies properly only when the ratio of crack length to sheet width is extremely small. The Greenspan-Irwin analysis is presumably more accurate than the Griffith analysis, since it takes into account (although not exactly) the ratio of crack length to sheet width. For a vanishingly small ratio of crack length to sheet width, the Greenspan-Irwin analysis is identical to the Griffith analysis.

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IBM-610 COMPUTER ACQUIRED

The Civil Engineering Department has just completed arrangements for leasing an IBM-610 Automatic Decimal Point Computer. This computer was designed to meet "a growing need for small computers which will solve problems in the area of computation between that of the desk calculator and that of the large electronic computer. Many of the problems in this intermediate range of computation stem from the normal routine of technical activity."

One attractive feature, which enhances the value of this type of computer, involves the re-use of the program tape for other problems of the same type. This flexibility is of special importance in optimizing a structure for either weight or stiffness.

This new equipment will be housed in More Hall and will be available to other divisions of the College of Engineering. The IBM Corporation will sponsor a short period of indoctrination in its use. During the next two quarters a graduate research assistant will be in charge of the computer in order to facilitate the instruction of a maximum number of users.

A FUEL METERING SYSTEM FOR DIESEL TRUCKS

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Assistant Professor of Mechanical Engineering

J. C. Firey

One phase of a recent Truck Utilization Survey* conducted jointly by the Civil and Mechanical Engineering Departments of the University of Washington was the development of a system for measuring the fuel consumption of diesel-powered trucks. The survey was in fulfillment of a contract between the University and the U. S. Bureau of Public Roads. Inquiries received indicate that publishing the details of the metering system may assist other agencies involved in similar studies.

Briefly, the requirements of the metering system were as follows:

1) The basic meter was to be adaptable to all types, makes, and sizes of trucks, both gasoline and diesel powered.
2) Physical dimensions were to permit installation in truck cabs without crowding the driver or observer.
3) Weight was to be kept to a reasonable minimum to facilitate handling and installation.
4) Installation was to require a minimum of time and labor to avoid undue delaying of truckers' schedules.
5) Installation was to require no physical alterations to the truck engine or body structure.
6) Instrumentation was to be rugged enough to withstand constant jolting and rough handling.
7) Arrangements for by-passing or quick disconnection of the meter, in the event of malfunction, were necessary since a breakdown would be costly to the truck operator.

A basic meter unit suitable for use on gasoline trucks and on diesel trucks with non-recirculating fuel systems was developed. The meter was connected, through the use of hoses, to the fuel system at the carburetor or fuel pump.

Diesel engines with recirculating fuel systems (e.g., a Cummins engine with a PT fuel pump) required certain modifications. The recirculating fuel meter interposed a small volume day tank between the engine and the main fuel-supply tank. The engine fuel pump drew only from this day tank and all excess recirculated fuel was returned to it. Fuel consumed by the engine was drawn from the day tank, but a constant level was maintained by supplying additional fuel from the main supply tank through a basic fuel-meter unit. In this manner the basic fuel meter recorded the quantity of fuel consumed by the engine.

H. T. Meador

Two methods of regulating the fuel level in the day tank were tried: a float valve and a float-actuated switch. Owing to certain "nuisance" types of difficulties encountered with the float valve, the float-actuated switch was used for most of the road testing. Nevertheless, the float valve is considered the more accurate and versatile arrangement, and will be discussed briefly later in this paper.

With a float-actuated switch, when the fuel level in the day tank dropped, the switch turned on an auxiliary electric fuel pump which pumped fuel from the main supply tank, through the basic meter unit, and into the day tank. The difference in fuel level within the day tank between the pump-on and pump-off positions of the float was about 0.1 gallons. The error introduced by this level difference was about five per cent for an eight-mile run, becoming smaller for longer runs.

The float-actuated switch consisted of a balsa wood float with attached switch-actuating bar and a snap switch. The float was sealed with oil-resistant lacquer to prevent fuel soaking into the wood. A washing-machine water-level switch was chosen because it required only a small force to trip and was dependable. It was connected in the grounded side of the electrical system so that failure would not short-circuit the truck's electrical system. The switch-actuating bar held two adjustable collars that tripped the switch. The schematic diagram shown in Fig. 1 indicates the various connections for the recirculating fuel meter.

* Professors R. G. Hennes and R. B. Sawhill, of the Civil Engineering Department, were Project Director and Project Supervisor, respectively, of the Truck Utilization Survey.

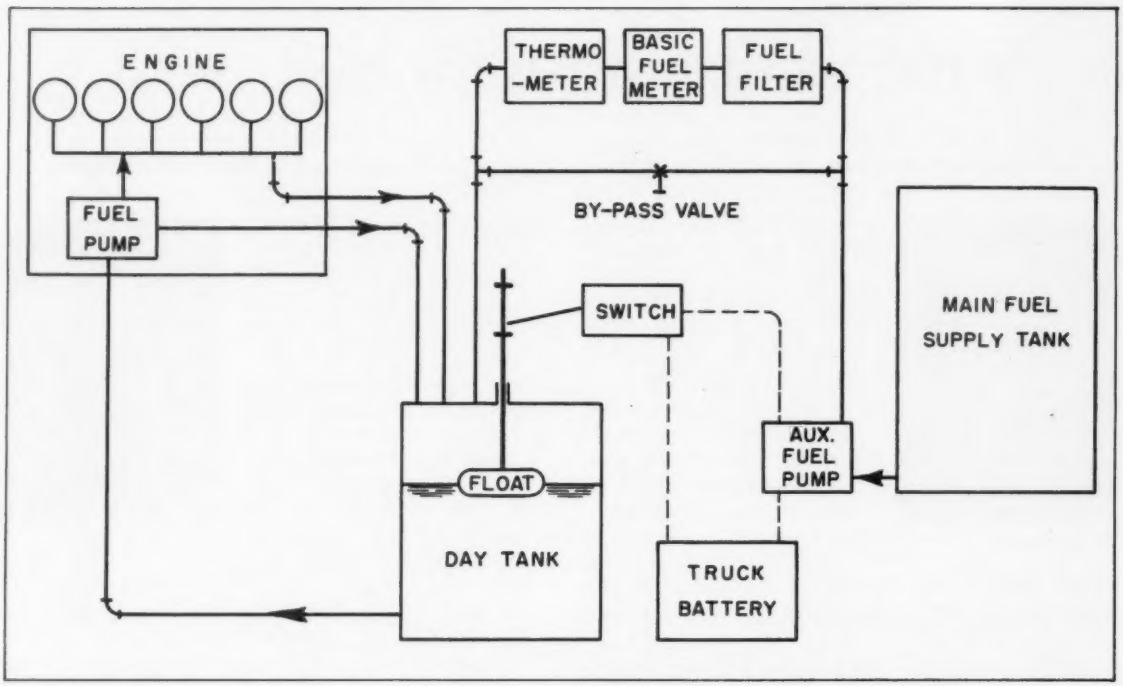

FIG. 1. SCHEMATIC DIAGRAM OF RECIRCULATING FUEL METER

It was found desirable to mount the day tank on the truck running board so that recirculated fuel could be cooled by atmospheric air. (See Fig. 2.) With an interior-mounted day tank, recirculated fuel temperatures rose to about 140° F, resulting in appreciable loss of engine power output. Even with the running-board mounting, fuel temperatures occasionally rose to 120° F and some power loss was noted. This difficulty could probably be avoided by providing finned coolers on both of the fuel return lines to the day tank.

The day tank was provided with a vent to permit the escape of fumes entrained in the recirculated fuel. These appeared to be combustion gases picked up at the fuel injectors in the engine.

Time did not permit the development of a satisfactory float valve, although the difficulties encountered with this arrangement were minor, consisting of leaking floats and excessive float inertia. These difficulties could probably be eliminated by using a truck carburetor float and valve. With such an arrangement the auxiliary fuel pump would run continuously, but fuel would be admitted to the day tank only when the float valve opened. This operation is identical to the action of the float valve and fuel pump on a gasoline engine. A float valve would maintain a very nearly fixed fuel level in the day tank

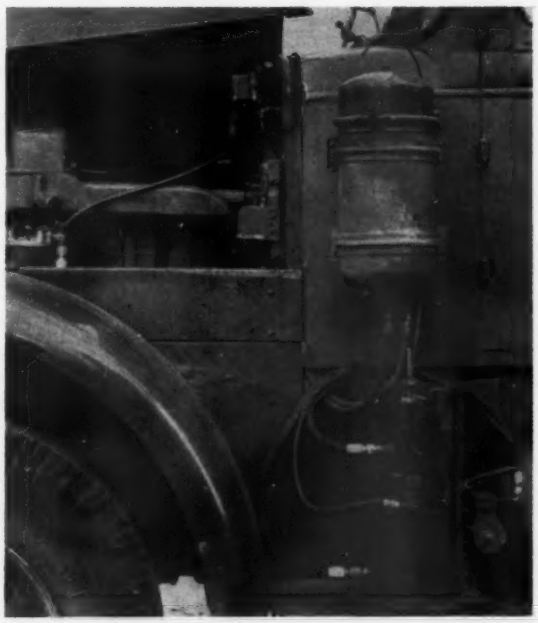

FIG. 2. VIEW OF DAY TANK MOUNTED ON RUNNING BOARD OF A DIESEL TRUCK

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and the error due to change in the level would be eliminated.

On some trucks the level of the fuel in the main fuel tank could be well above that of the fuel in the day tank. In that event the float-actuated switch could not be used since flooding of the day tank could not be prevented. The float valve would operate satisfactorily under those conditions and thus would be more versatile.

A problem peculiar to truck road testing is the necessity that the instrumentation be reliable and foolproof on the first few trial runs. A rather minor instrument failure, such as a leaking float, ties up a truck with cargo and driver for several hours, resulting in unreasonable expense to the cooperating truck owner. Nevertheless, a road-test evaluation of the instrumentation is needed since a device which works perfectly in the laboratory will frequently fail unexpectedly when run on the road.

In road tests, the recirculating fuel meter, as described with float-actuating switch, functioned in an entirely satisfactory manner.

The Trend in Structural Analysis

(Continued from page 9)

or the deformation method of formulation may be used to reduce the size of the matrices involved. Formulation by the force method reduces to the analysis of a statically determinate structure under several unit loads to determine $[b_0]$ and $[b_1]$. This formulation of the problem, together with the digital computer, will eventually make possible the analysis of structures in a much more economical manner and will therefore aid in freeing the architect from restrictions on form. Perhaps the greatest result of the unification of the diverse approaches to structural analysis into a single method is a clear understanding of the classical methods. We might recall the words of a leading structural engineer and professor of civil engineering at the Massachusetts Institute of Technology who remarked that an important job for structural engineers in the future is the adoption of the methods of analysis developed for complex aircraft. It is interesting to note that most issues of the *Journal of the Structural Division* of ASCE contain an article on application of digital computers to structural analysis, as for example Reference (7), and that an entire meeting of the Structural Division is being devoted to the use of the digital computer.

The ideas presented here are not new but have been slowly developed over the last century. A more complete survey of the status of structural analysis has been made by J. H. Argyris.[8] A complete bibliography on structural analysis can be found in References (7) and (8). A complete and elegant comparison of the force and deformation methods is contained in Reference (5). The force and deformation methods are presented in text-book form in Reference (9).

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RESEARCH CONTRACTS RENEWED

The University research contract with the U.S. Atomic Energy Commission for support of research entitled "Separation Efficiency of Pulsed Extraction Columns" has been renewed for Part III of the project, to cover the year 1959. The grant is $17,343.00, an increase of $5,470.00 over the grant for 1958, in order to provide funds for additional equipment, and salary for a post-doctoral fellow. A graduate student will also be sent to Hanford during the summer to work on a cooperative program. Dr. A. L. Babb, of the Department of Chemical Engineering, is chief investigator. His assistant will be Dr. B. W. Mar.

Dr. Babb is also in charge of the project entitled "Fundamental Studies of Chemical Absorption," which has been sponsored by the National Science Foundation. This program also has received a contract renewal with a grant of $14,300.00 to cover the next two years.

Engineering Research Dividends

Recent theses submitted for advanced degrees from the College of Engineering, University of Washington, will regularly appear in abstract form in *The Trend*. Complete copies of these theses are available for reference at the University of Washington Library. Address inquiries to the Director of the Engineering Experiment Station, University of Washington, Seattle 5.

JOHNSTON, IVENE M., "An X-Ray Diffraction Study of Kaolin Minerals." M.S. in Ceramic Engineering, 1958.

An X-ray diffraction study of kaolin minerals was performed using a G-M tube detector, an electronic counting and scaling unit, and a Brown strip-chart recorder. The data thus acquired were compared with the results obtained by other workers, all of whom used camera techniques. Sixty-one reflections are reported for Lewistown kaolinite, which is an increase of 28 over those reported by the API for the same mineral, and an increase of 13 reflections over the pattern reported by Brindley. Five reflections cannot be accounted for by Brindley's calculated pattern. The experimentally determined patterns for Zettlitz kaolin and Edgar's plastic kaolin are given, both of which have not been previously reported. The experimentally determined patterns for five halloysites are reported, and the agreement with previously reported patterns is generally poor. For three of the halloysites an increase in the number of reflections is reported in this investigation.

A literature review of previous X-ray work on kaolin minerals is included.

TAYLOR, R. E., "Verification of Folded-Plate Theories." M.S. in Civil Engineering, 1958.

The economy of material inherent in long-span folded-plate roof structures has greatly accelerated their use in recent years. Several methods of analysis for this type of structure have been proposed but only one has been verified by experimental evidence. This study was an attempt to determine the validity of these methods.

For this purpose, a testing device was constructed and a series of model tests performed to simulate the behavior of plywood, thin metal, and reinforced concrete folded plates. The results showed that the engineer can, with discretion, safely use the various methods of analysis in the design of folded-plate structures.

In addition, a simplified method of analysis was developed for the general case of a concentrated load on a monolithic folded plate. Stresses and deflections predicted by this method agreed well with the experimental results.

SNARING, T. M., "Comparative Survey of Methods of Analysis for Complex Aircraft Structures." M.S. in Aeronautical Engineering, 1958.

This thesis presents a discussion of various methods for the analysis of complex aircraft structures. These methods are compared with respect to the determination of stresses and deflections, and particular methods of analysis are suggested as being the most practical to use in each area. The comparison is made with regard to the accuracy obtainable by each specific method and also to the adaptability and economy to the specific area concerned.

The Levy stiffness method was concluded to be, in general, the most practical method for the determination of the stresses in complex aircraft structures, while the Turner, Clough, Martin, and Topp stiffness method is the most practical for the determination of the deformations of the structure. Advantages and disadvantages of all the methods with regard to the determination of stresses and deflections are discussed.

An example problem is presented in the appendix to illustrate the practical applications of the methods of analysis considered, and the stresses and deflections for both pure bending and pure torsion of the structure obtained by each method are compared and discussed.

GROVER, S. K., "The Effect of Low Temperature Upon the Fatigue of Notched A7-46 Steel." M.S. in Civil Engineering, 1958.

The purpose of this investigation was to study the fatigue life of notched A7-46 steel specimens at room temperature, -50° F, and -70° F. Thirteen steel

(Continued on page 24)

New Projects

Project No. 230. High-Temperature X-Ray Studies. Supervisor: J. I. Mueller, Professor of Ceramic Engineering; Research Assistant: A. D. Miller

Project No. 231. Kinetic Studies of Ion Exchange Cu-Na-Dowex 50 Systems. Supervisor: J. L. McCarthy, Professor of Chemical Engineering; Research Assistant: G. M. Rao.

Project No. 232. Folded Plate Roofs of Plywood Sheathed Diaphragms. Supervisor: A. L. Miller, Professor of Mechanics and Structures; Research Assistant: R. E. Taylor.

Project No. 233. Wave Research Study. Supervisor: J. C. Kent, Assistant Professor of Civil Engineering; Research Assistant: T. Hirota.

Project No. 234. Effects of Low Temperature on Notch Sensitivity. Supervisor: D. D. Vasarhelyi, Associate Professor of Civil Engineering; Research Assistants: S. K. Grover and M. H. Kashani-Sabet.

Project No. 235. Conditionally Stable Servomechanism Systems. Supervisor: R. N. Clark, Assistant Professor of Electrical Engineering; Research Assistant: T. J. Manetsch.

Project No. 236. Physics of Engine Knock. Supervisor: J. C. Firey; Associate Professor of Mechanical Engineering, Research Assistant: R. R. Lavi.

Project No. 237. Local Velocities and Heat Transfer in the Natural-Convection Flow of Water. Supervisor: P. J. Waibler, Associate Professor of Mechanical Engineering; Research Assistants: Y. Tuan and M. Van Dyke.

Project No. 239. Traveling Wave Antennas. Supervisor: G. Held, Associate Professor of Electrical Engineernig; Research Assistants: R. V. Hill and J. Blundell.

Project No. 241. Design, Assembly, and Check-out of Data-Taking Equipment for Shock Tunnel. Supervisor: R. E. Street, Professor of Aeronautical Engineering; Research Assistant: E. W. Robinson.

Project No. 243. Experimental Investigation of a Jet Flap. Supervisor: V. M. Ganzer, Professor of Aeronautical Engineering; Research Assistant: H. G. Ahlstrom.

Project No. 244. Measurement of Lattice Constants for Subcritical Reactor I. Supervisor: A. L. Babb, Associate Professor of Chemical Engineering; Research Assistant: W. E. Wilson.

Project No. 245. The Production of Titanium Compounds by Electrolysis of Fused Salts. Supervisor: R. W. Moulton, Professor of Chemical Engineering; Research Assistant: F. S. Ardeshir.

Project No. 246. Phase Transformation Studies in Copper-Silicon Alloys. Supervisor: D. H. Polonis, Associate Professor of Mineral Engineering; Research Assistant: G. A. Dreyer.

Project No. 247. Plate Girder Study. Supervisor: D. D. Vasarhelyi, Associate Professor of Civil Engineering; Research Assistants: J. C. Taylor and C.Y. Yuan.

Project No. 248. Exponential Experiments in a Graphite-Natural Uranium Reactor. Supervisor: A. L. Babb, Associate Professor of Chemical Engineering; Research Asistant: W. A. Blyckert.

Project No. 249. High-Temperature Chlorination in a Fluidized Bed. Supervisor: L. N. Johanson, Associate Professor of Chemical Engineering; Research Assistant: J. C. Almond.

Project No. 250. Investigation of Anaerobic Digestion Reaction Kinetics. Supervisor: R. H. Bogan, Associate Professor of Civil Engineering; Research Assistant: R. R. Heinke.

Project No. 251. Lunar Tidal Studies. Supervisor: H. M. Swarm, Associate Professor of Electrical Engineering; Research Assistant: N. N. Rao.

Project No. 252. Information Theory Applications to Antenna Synthesis. Supervisor: H. M. Swarm, Associate Professor of Electrical Engineering; Research Assistant: P. A. Lux.

Project No. 253. Study and Development of an Electronic Print Reading Device. Supervisor: D. L. Johnson, Associate Professor of Electrical Engineering; Research Assistant: J. C. Windell.

Project No. 254. Slot Jet Mixing. Supervisor: M. E. Childs, Associate Professor of Mechanical Engineering; Research Assistants: H. W. Ip and L. J. Tisher.

Project No. 255. Satellite Re-entry into the Atmosphere. Supervisor: R. E. Street, Professor of Aeronautical Engineering; Research Assistant: R. P. Edwards.

Project No. 256. Installation, Alteration, and Calibration of the 3" x 3" Mach 5 Wind Tunnel. Supervisor: V. M. Ganzer, Professor of Aeronautical Engineering; Research Assistant: A. S. Mahal.

Project No. 257. Boundary-Layer Transition in Natural Convection. Supervisor: P. J. Waibler. Associate Professor of Mechanical Engineering; Research Assistant: J. R. Larson.

Project No. 258. Longitudinal Diffusion in Solvent Extraction Columns. Supervisor: A. L. Babb, Associate Professor of Chemical Engineering; Research Assistant: G. A. Sehmel.

Needed: A Wider Lens

(Continued from page 1)

is being severely criticized today by its public. Parental objection to the arbitrary and difficult entrance examinations has even resulted in suits against the government of several German states for barring children from a pre-university school. The screening process, originally made at age 10 to 11, has been postponed in some states, and in one state election the length of the school course became a major election issue. Here, too, the American democratic plan may have provided the initial thrust, with results that sound familiar to our ears.

Red China. Awareness of the terrific tempo of industrialization and education in the 600 million people of Red China is just appearing on our horizon. Perhaps we should be more alert than we were with respect to Russia. The 200 colleges and universities on the mainland have 480,000 students, but Red China, unlike Russia, has had to start from the very beginning. One lesson in Mao's modernization primer, for instance, shows how a wheelbarrow can free two men for tasks that cannot be done with a shoulder-pole. J. Tuzo Wilson, President of the International Union of Geodesy and Geophysics, who recently visited Lanchow, reported on its explosive activity and the "staggering" amount of construction which is made possible by the labor of housewives and of night-shifts of students and office workers. One notable feature is the Institution of National Minorities, where students from 16 of China's 51 minorities go to school, for one of China's most serious problems is that of its numerous indigenous languages. In this Institute an assembly room provides 1700 seats, each equipped with earphones for simultaneous translation in four languages. The school libraries of Red China have hundreds of thousands of volumes, laboratory equipment is good, and courses are being lengthened as students qualify for higher levels.[11]

Red China's progress, though based on remorseless disregard for the individual—even to estimating that half its population is expendable, if necessary—has kindled a flame of fanatic purpose that will bear watching.

Where Do We Stand? We in the United States have an educational system that is, theoretically and basically, sound. In probably no other country are opinions so generally and copiously expressed. Our difficulty is not in planning improvements but in putting them into effect. "In this most agonizing time . . . no major change in scientific education has received the support of the federal government or of industrial financial resources."[12] We are almost the only country whose educational processes are not determined by experts or the "intellectual crust." Our educational legislation may depend, for instance, on the vote of such a man as Senator George D. Aiken of Vermont who asked last year in a meeting of the Foreign Relations Committee, "Who would like to see the Senate of the United States run by ninety-six Phi Beta Kappas?"[13] Senator Aiken might have been reminded that eleven of his colleagues were Phi Beta Kappas, including some of the hardest-headed and most influential politicians. Eleven of our 34 Presidents have been members of this honorary.

Again, public opinion, while often an admirable brake on too hasty action, can prevent local innovations which might increase the efficiency of our school systems. Suggestions by school authorities of tougher requirements for entrance to state institutions of learning are condemned as "undemocratic" by parents, with reminders that "we pay the taxes." Resistance to a plan to lengthen the public school year has stemmed in some cases from a dislike of upsetting family vacation plans. Possibly most serious of all is the lack of aggressive support of educational programs that involve realistic spending.

Dean Burchard of M.I.T. has said, "I believe we make our task more difficult when we do permit and even encourage such discussion in our education, but on the day when we discontinue such efforts I believe we shall have lost our primary advantage over our competitors."[14] Quite true, but discussion should be based on full information and directed toward the general good. Dr. Simon Ramo, top scientist of the Air Force's IBM and Space Programs, stated, at the annual meeting of the ASEE last June, that the threat of Russia's passing us in the technological race through more concentration on education is greater than the immediate danger to our nation from Soviet space advances, and that if we gave the same emphasis to education that we give to missiles and space, we could have vastly superior technology in a decade.

Effective emphasis on education will require more than our financial support. It will require us to adjust our vision to a world-wide screen.

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EFFECT OF LOW TEMPERATURE ON STEEL

(Continued from page 22)

specimens with various notches were tested, all cut from the same plate and with the mill scale left intact. The tests were conducted at a constant stress level and the number of cycles at which the specimen fractured was recorded, thus obtaining a relationship between the sharpness of the notch and the fatigue life for the ambient temperatures.

The purposes of the experiment were further extended to determine if the fatigue life of these specimens were related to the static tensile strengths at room temperature, -50° F, and -70° F. Four tests for static tension were conducted in this series. Two welded specimens with notches were also tested, one at room temperature and one at -50° F.

The fatigue life of both welded and unwelded notched specimens increased with decrease in temperature, the amount of increase depending mainly on the sharpness of the notch. The tensile strength also increased with decrease in temperature.

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